

Anisotropic Zeeman Splitting In Ballistic One-Dimensional Hole Systems

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Abstract.

We have studied the effect of an in-plane magnetic field B on a one-dimensional hole system in the ballistic regime created by surface gate confinement. We observed clearly the lifting of the spin degeneracy due to the Zeeman effect on the one dimensional subbands for B applied parallel to the channel. In contrast, no Zeeman splitting is detected for B applied perpendicular to the channel, revealing an extreme anisotropy of the effective Landé g -factor g^* . We demonstrate that this anisotropy is a direct consequence of the one-dimensional confinement on a system with strong spin-orbit coupling.

It has been proposed to exploit the intrinsic coupling between the spin and orbital motion of quantum particles to control spin-splitting with an electric field [1], offering new opportunities to implement a spintronic paradigm [2]. The ability to control the spin-splitting with an external electric field has led to proposals for a spin-field-effect transistors [3] which could be used to perform new kinds of logic operations.

Electric-field-tuneable spin-orbit (SO) interactions for electrons arise through the coupling between conduction and valence band that is induced by structural inversion asymmetry. Consequently, such SO effects are larger in narrow-gap materials such as InGaAs and InAs. However, the small band gap makes it difficult to use conventional metal surface gate technique, due to the absence of a Schottky barrier, to create nanostructures for electrical field control of spin studies. An alternative is to use holes rather than electrons in a wider gap material. In a tight binding view, as valence-band states are predominantly p-like (unlike conduction-band states which are s-like), SO effects are particularly important in low-dimensional hole systems such as p -type GaAs, making this material system interesting for spin-controlled devices.

In bulk, zinc-blende compounds such as GaAs, SO coupling causes splitting of the top-most valence band in four fold degenerate heavy and light hole state (with total angular momentum $J = 3/2$) and the two fold degenerate split off state (with total angular momentum $J = 1/2$). However, two dimensional (2D) confinement lifts the heavy hole (HH)-light hole (LH) degeneracy at $k = 0$.

As a result the carrier transport is predominantly through the HH subband. In addition, the confinement gives rise to mixing ($k \neq 0$) and non-parabolicity of the HH and LH subbands (for a complete review see [4]).

We have studied how confining holes in a 1D channel affects their spin properties. We used the intrinsic conductance quantization properties of ballistic one-dimensional (1D) systems to probe the 1D subband edges and studied the effect of an in-plane magnetic field B . We have performed Zeeman splitting measurements in a ballistic 1D hole system aligned along the $[233]$ direction and formed in a GaAs (311)A quantum well by surface gate confinement (see [5] for description of the device). Application of an in-plane magnetic field parallel (B_{\parallel}) to the wire lifts the spin degeneracy and eventually causes the 1D subbands edges to cross. Figure 1 clearly shows the splitting of the subband edges (white regions) in the transconductance grayscale plot (dG/dV_{SG} as a function of side gate voltage V_{SG} and B ; the derivative has been numerically calculated from the differential conductance G corrected for a series resistance). After thermal cycling and sample re-orientation, we have studied the effect of an in-plane magnetic field perpendicular to the wire B_{\perp} . In contrast, the transconductance grayscale (Fig. 1(b)) shows that the degenerate 1D subbands are not affected by B_{\perp} up to 8.8 T, *i.e.* no Zeeman splitting is seen when the magnetic field is aligned perpendicular to the channel.

Combining Zeeman effect measurements and source-drain bias spectroscopy, and knowing that the spin-

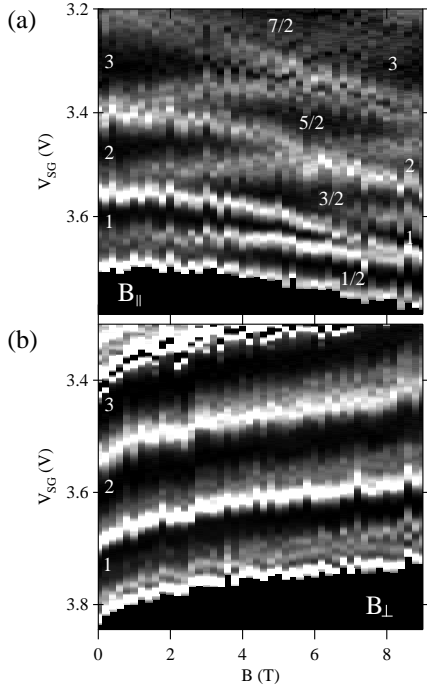
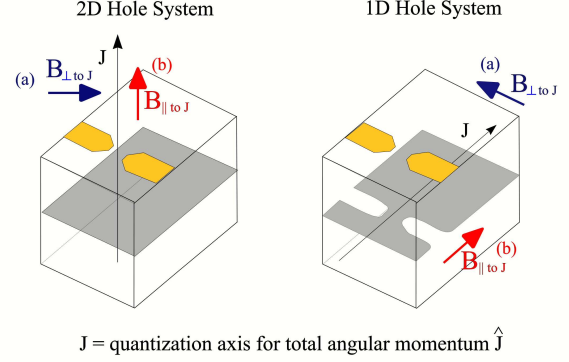


FIGURE 1. Zeeman effect in a 1D hole system: (a) Transconductance grayscale as a function of V_{SG} and B_{\parallel} ; black regions correspond to low transconductance (*i.e.* conductance plateaus, labelled in units of $2e^2/h$), white regions correspond to high transconductance (subband edges): splitting of the 1D subbands is clearly observed. (b) Transconductance grayscale as a function of V_{SG} and B_{\perp} : no Zeeman splitting is seen. Data are taken with a back gate and mid-line gate voltage of 2.5 and -0.225 V respectively (see [5] for description of the device).

splitting is linear in B (see [7]), one can extract the effective Landé g -factor g^* using the basic relation $\Delta E_N = g_N^* \mu_B B$ [6]. The g^* ratio $g_{\parallel}^*/g_{\perp}^*$ (*i.e.* for B_{\parallel} and B_{\perp}) can be estimated *at least* to be 4.5 [7], significantly larger than the anisotropy calculated [8] and measured [9] in 2D hole systems. One can explain this strong anisotropy by the following arguments. As mentioned above, only HH participate in the carrier transport in a 2D hole system. It has been demonstrated that Zeeman splitting is suppressed for a magnetic field applied parallel to a 2D hole quantum well, in which the total angular momentum axis J is aligned along the growth axis [10, 4]. Only a magnetic field applied along J generates the energy splitting due to the Zeeman effect for both HH and LH bands. *This is a result of strong SO coupling in the valence band.* In our system, the 1D confinement forces J to lie along the 1D constriction: this explains why no Zeeman splitting is measured for B applied perpendicular to the channel (see Fig. 2), though B applied parallel to the channel lifts the spin degeneracy of the 1D subbands.



(a) Suppression of HH Zeeman splitting if B is applied perpendicular to J
(b) HH Zeeman splitting if B is applied parallel to J

FIGURE 2. Sketch of the effect of a magnetic field perpendicular (a) and parallel (b) to the quantization axis for total angular momentum \hat{J} , on a 2D hole (as in [10]) and 1D hole system created by two side gates [7].

In conclusion, we have measured a strong anisotropy of the Zeeman splitting in a 1D hole system with respect to an in-plane magnetic field B oriented along or parallel to the channel. Our results show that confining holes to a 1D system fundamentally alters their spin properties, and that it is possible to tune the g^* anisotropy (as well as the absolute value of the effective Landé g -factor [7]), by electrostatically changing the width of the 1D system.

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